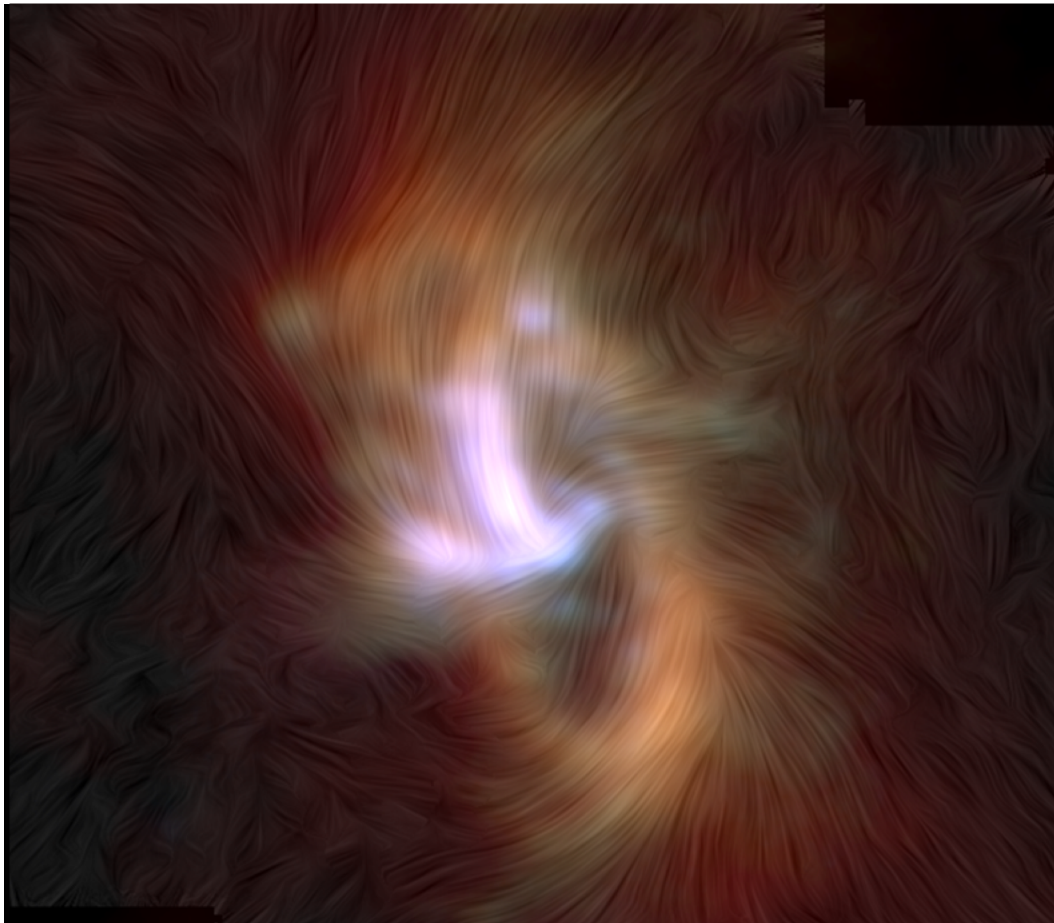


Credit: Lopez-Rodriguez, Lau & HAWC+ Science Team

Science in the SOFIA Era

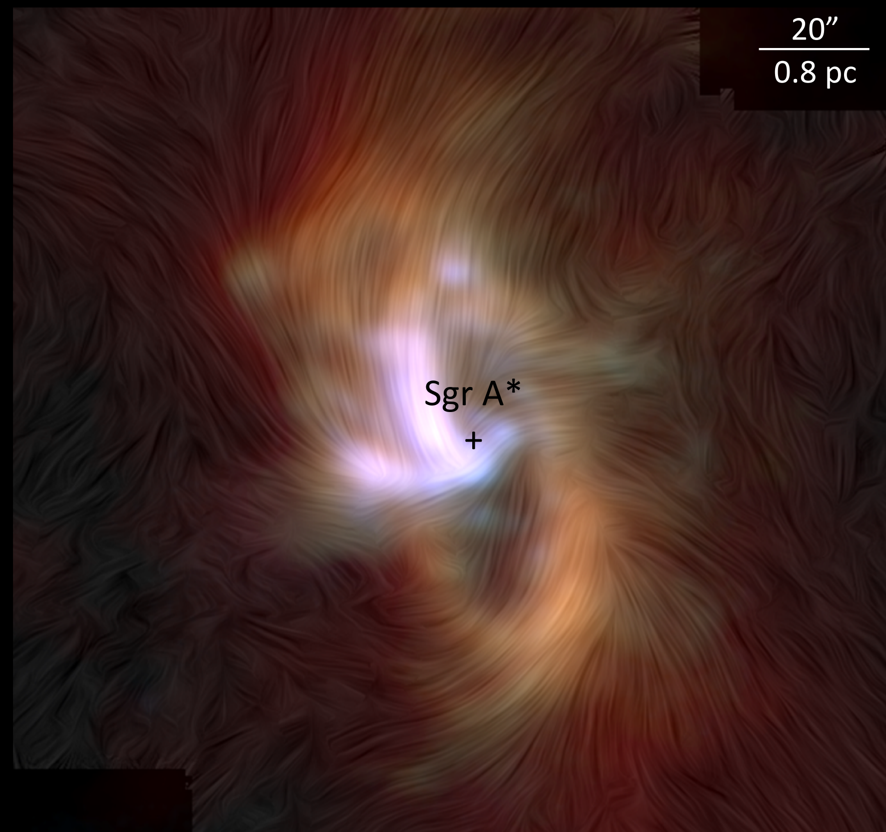
Harold Yorke
Director, SOFIA
Science Mission Operations

July 24, 2018

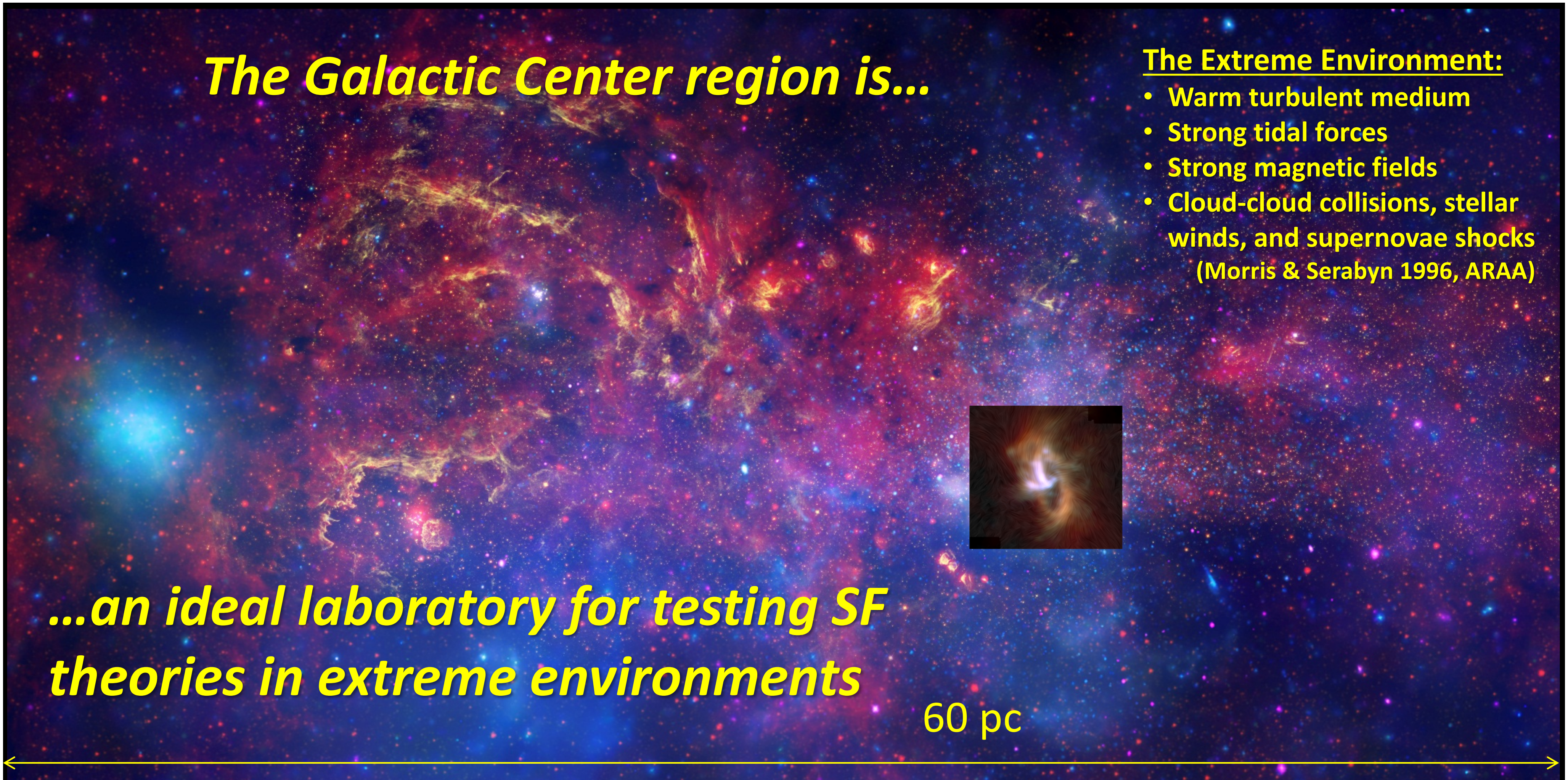
Stratospheric Observatory for Infrared Astronomy

Magnetic Field at the Galactic Center

- SOFIA/HAWC+ polarimetry at 53µm trace magnetic field lines
- SOFIA/FORCAST reveals arcs of dusty material surrounding and possibly feeding the massive BH
- How strong would the magnetic field have to be to affect the galactic center dynamics?
- Does the magnetic field control or even quench the flow to the massive BH?

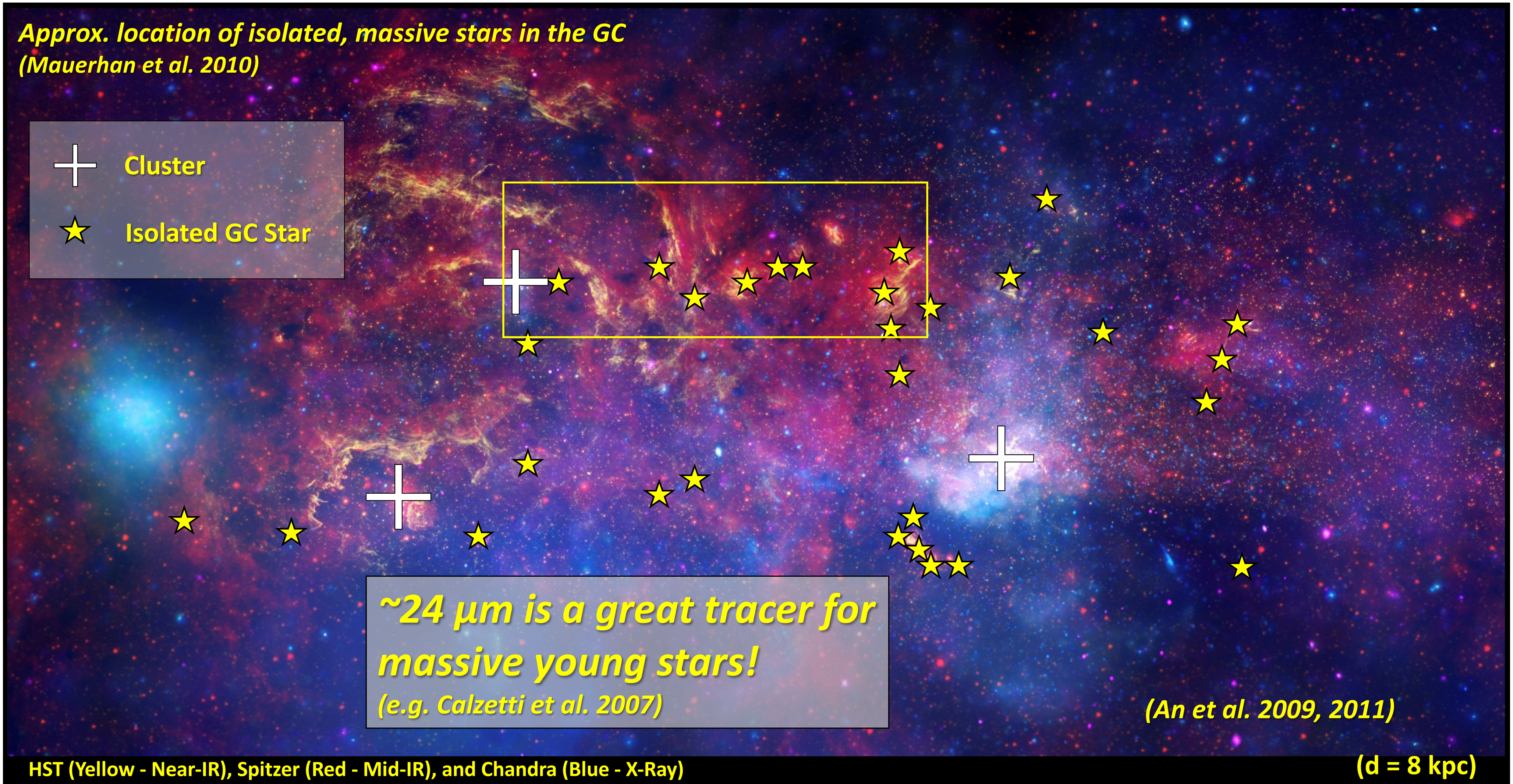


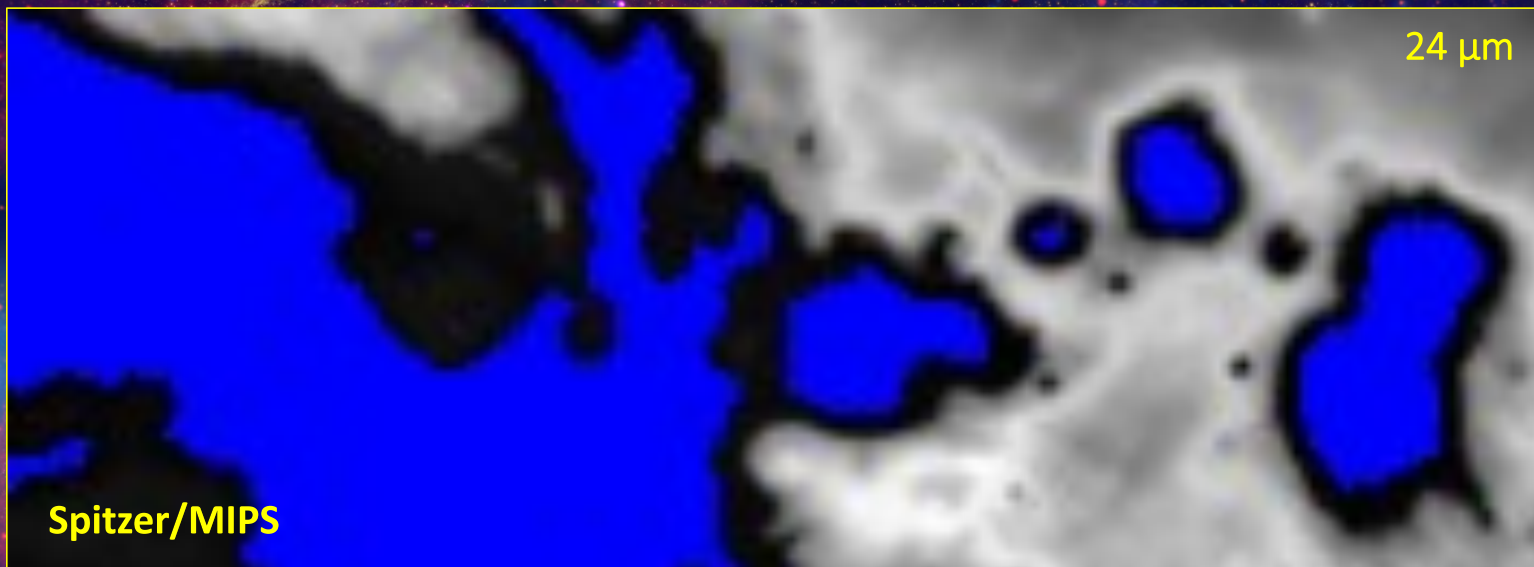
Lopez-Rodriguez, Lau & HAWC+ Science Team



HST (Yellow - Near-IR), Spitzer (Red - Mid-IR), and Chandra (Blue - X-Ray)

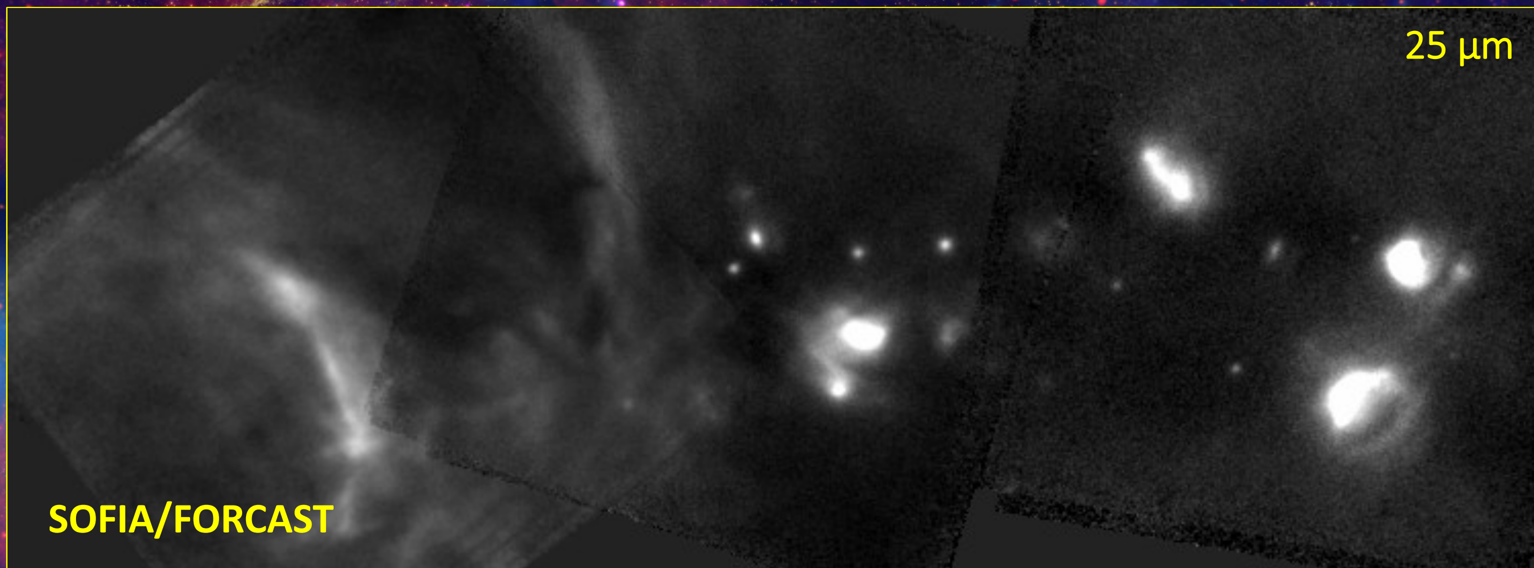
(d = 8 kpc)


Approx. location of isolated, massive stars in the GC
(Mauerhan et al. 2010)
Cluster
Isolated GC Star
~24 µm is a great tracer for massive young stars!
(e.g. Calzetti et al. 2007)
(An et al. 2009, 2011)
HST (Yellow - Near-IR), Spitzer (Red - Mid-IR), and Chandra (Blue - X-Ray)
(d = 8 kpc)



HST (Yellow - Near-IR), Spitzer (Red - Mid-IR), and Chandra (Blue - X-Ray)

(d = 8 kpc)



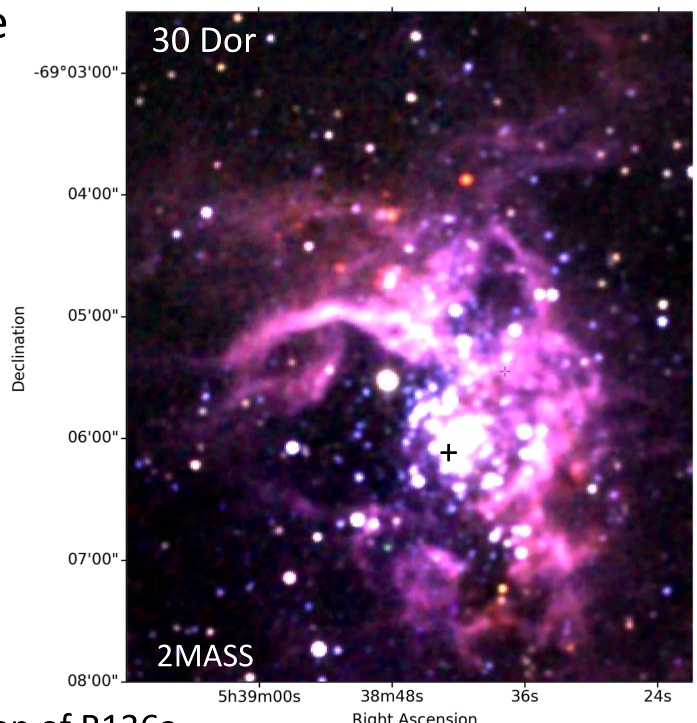
Hankins et al. *(Submitted)*

HST (Yellow - Near-IR), Spitzer (Red - Mid-IR), and Chandra (Blue - X-Ray)

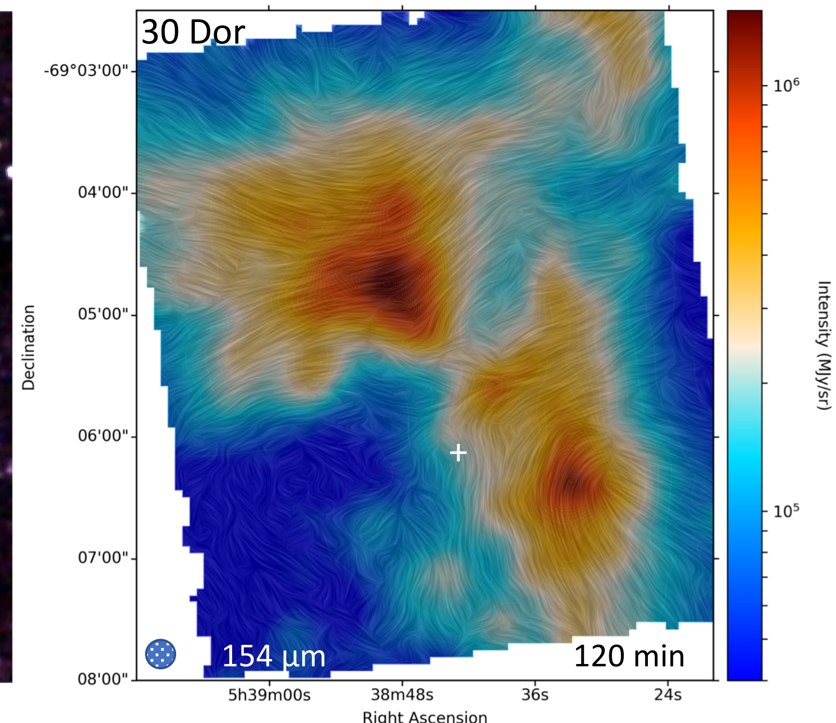
(d = 8 kpc)

Magnetic Field 30 Doradus Mini-Starburst

- Far-IR reveals intense star forming activity in 30 Dor
- Polarization/ photometric data reveal magnetic field structure in star forming molecular clouds in LMC
- Evidence of Parker Instability?



+ location of R136a



DDT observations: Non-proprietary HAWC+ data available for download Aug 2018

SOFIA/HAWC+ image prepared by Lopez-Rodriguez

Magnetic Field in Active Galaxies

Is the field channeling the plasma or is the plasma dragging the field?

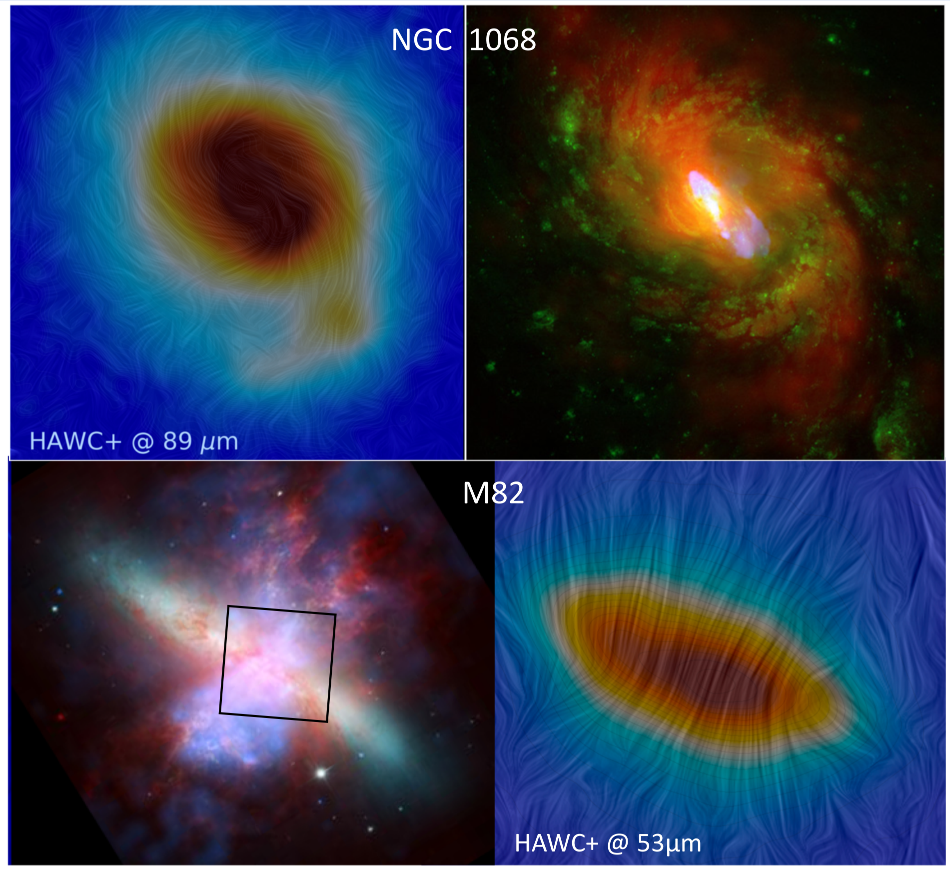
Active Galactic Nuclei

- Magnetic arms due to polarized emission from aligned dust grains => spiral magnetic fields

Starburst Galaxy

- Dusty galactic outflows driven by star formation => polar magnetic fields

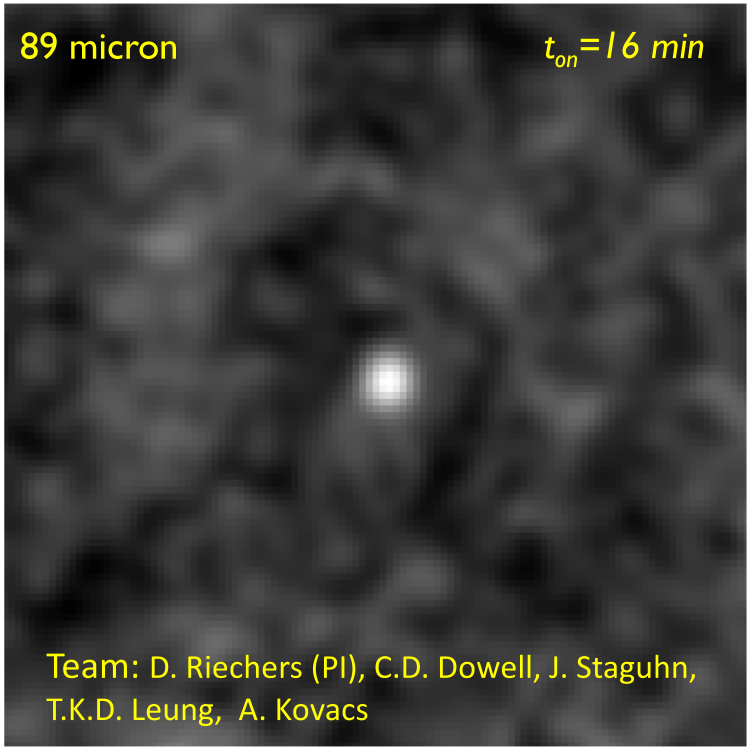
102 min



23 min

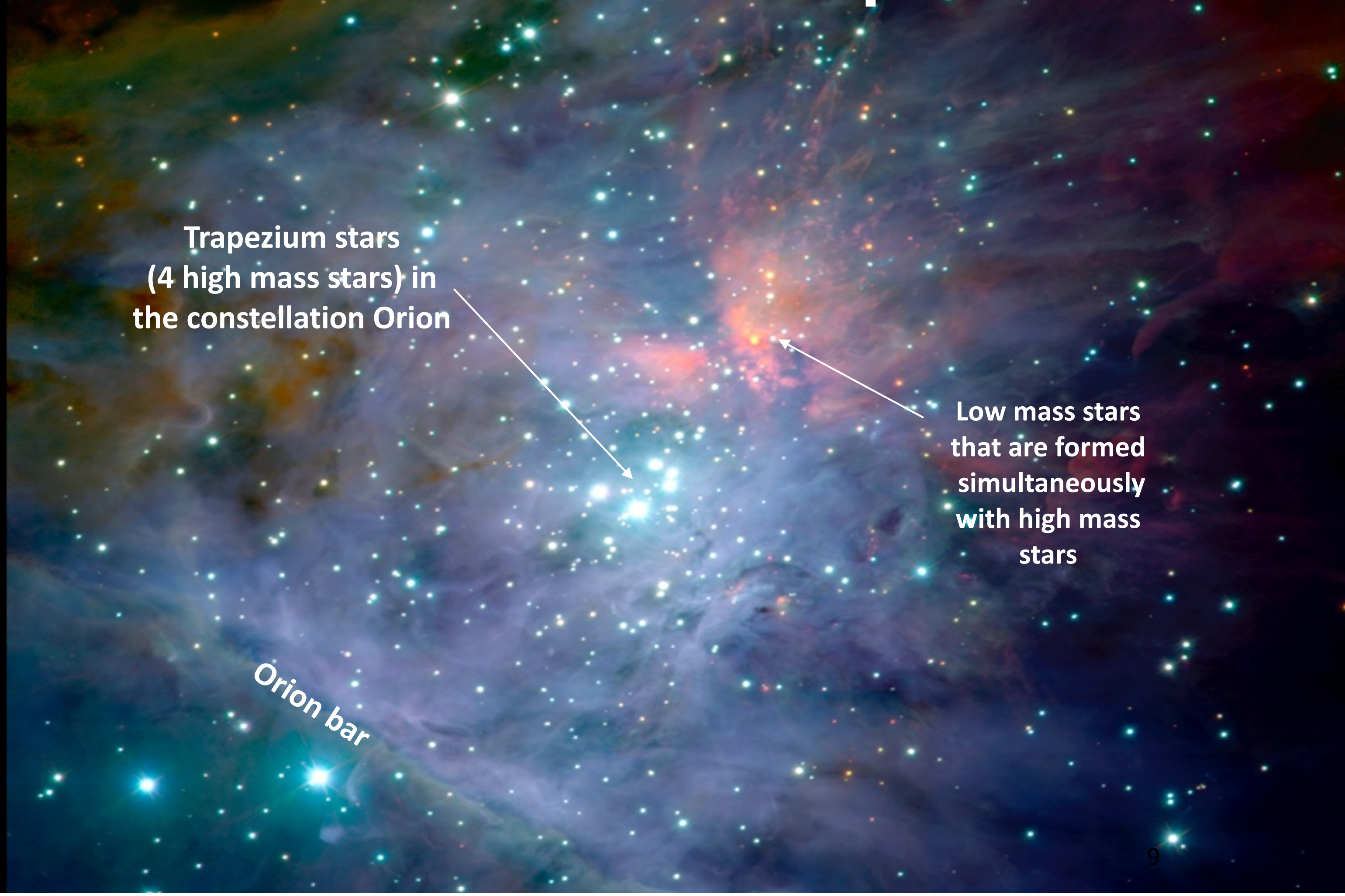
Dust Emission from Galaxy at z=3.9

- SOFIA/HAWC+ images of z=3.9 lensed galaxy APM08279 reveal strong star formation activity 1.6 Gyr after the Big Bang, dwarfing galaxy's AGN activity
- S/N ~10 for achieved at 53, 89 & 154µm
  (λ_{rest} : 11, 18 & 31µm) in <40min
- Observations provided information necessary to separate AGN from starburst contributions to the total energy
- Several dozens of bright lensed galaxies could be similarly analyzed using SOFIA

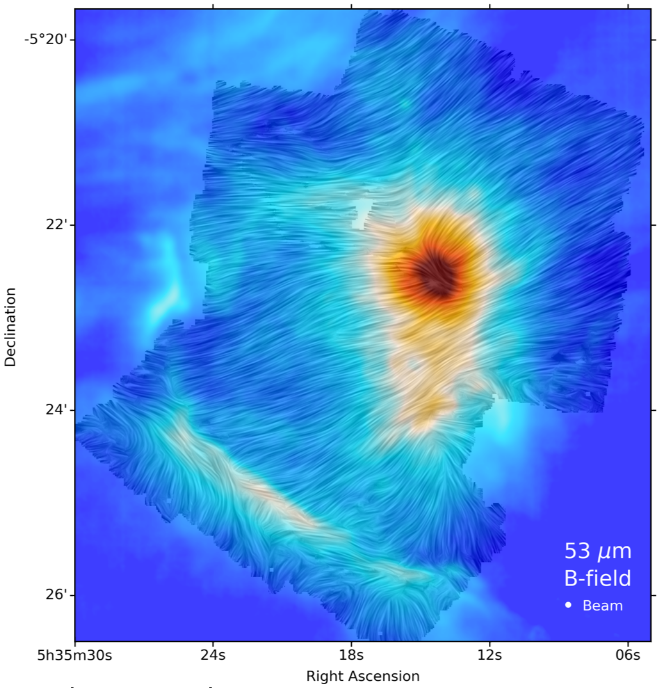


more lensed galaxies to be observed in Cycle 6

Nano-Starburst: Orion Trapizium Cluster



Use of multi-wavelength studies to untangle role of magnetic fields in star-forming regions: The case in Orion

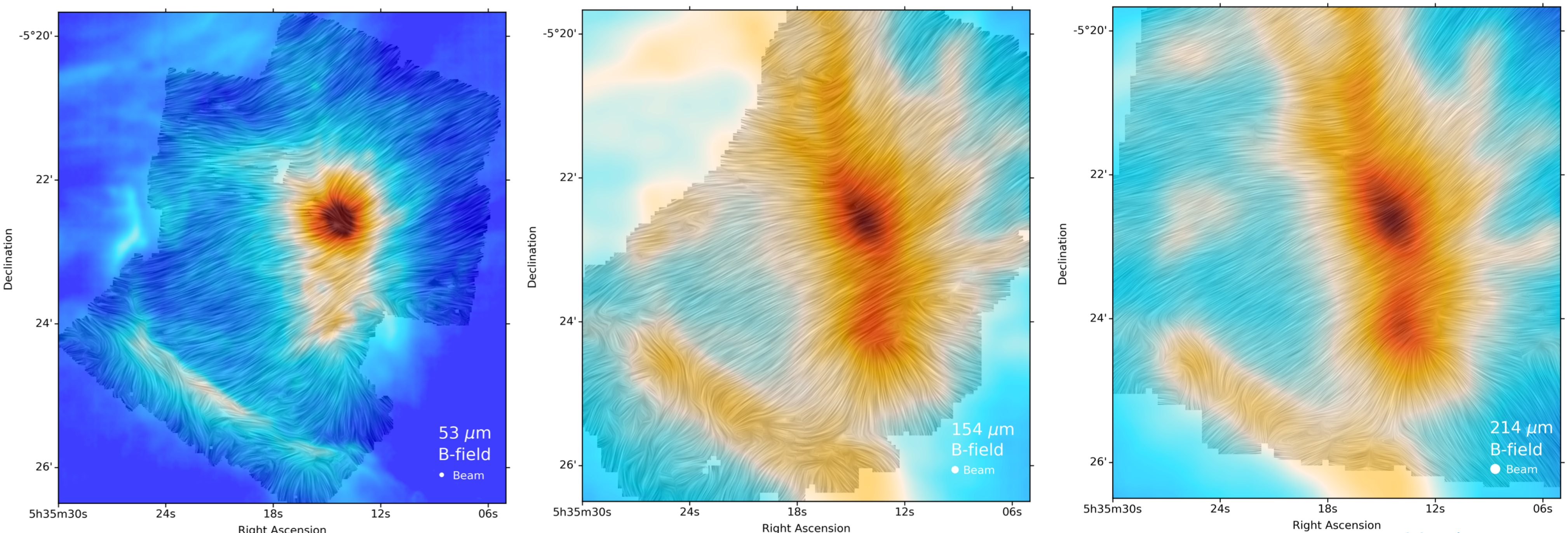


Chuss et al in prep

200 minutes

- Far-IR polarization of thermal radiation is due to emission of aligned dust grains
- Near-IR polarization has the component of scattered light; sub-mm & radio include synchrotron emission. Neither is present in the Far-IR
- Far-IR gives the orientation of magnetic fields at maximum emission of each wavelength

Use of multi-wavelength studies to untangle role of magnetic fields in star-forming regions: The case in Orion



Chuss et al in prep

200 minutes

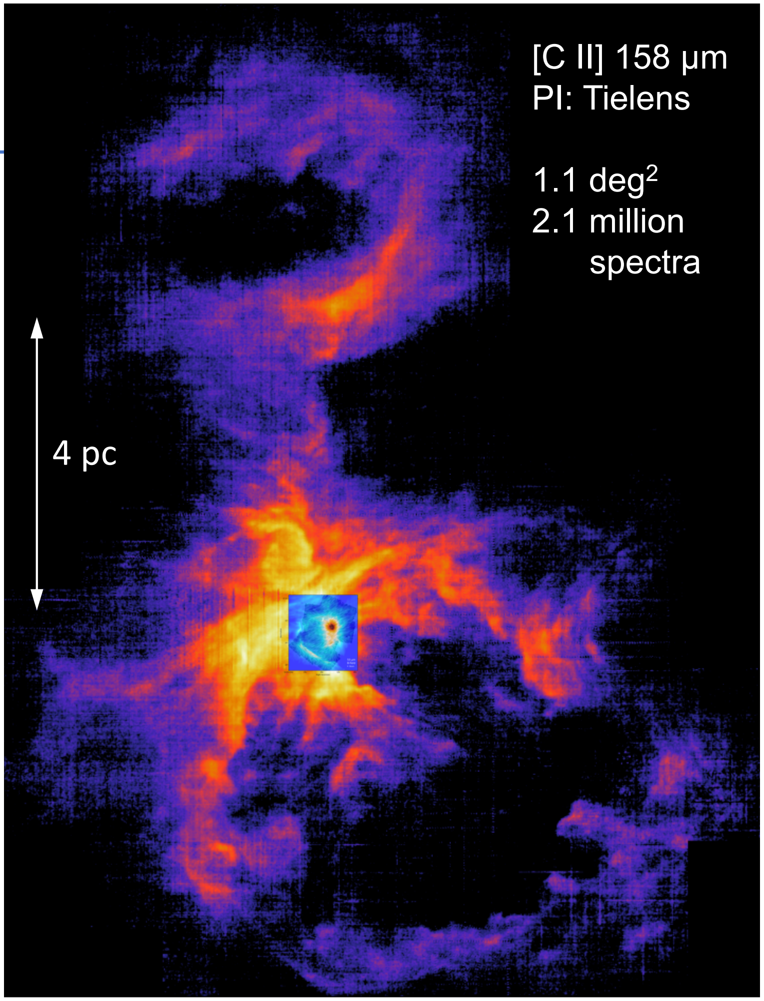
40 minutes

20 minutes

How the angle of the field changes with wavelength (different regions) has the potential to provide an insight into the 3-D morphology of the field structure.

[C II] Emission in Orion

- Use [C II] as a tracer of the star formation rate (validate & calibrate)
- Measure the molecular cloud mass not found by CO (“CO-dark” gas)
- Determine bulk kinematics & turbulence in this gas
- Find the photo-electric heating efficiency over a wide range of incident UV fields

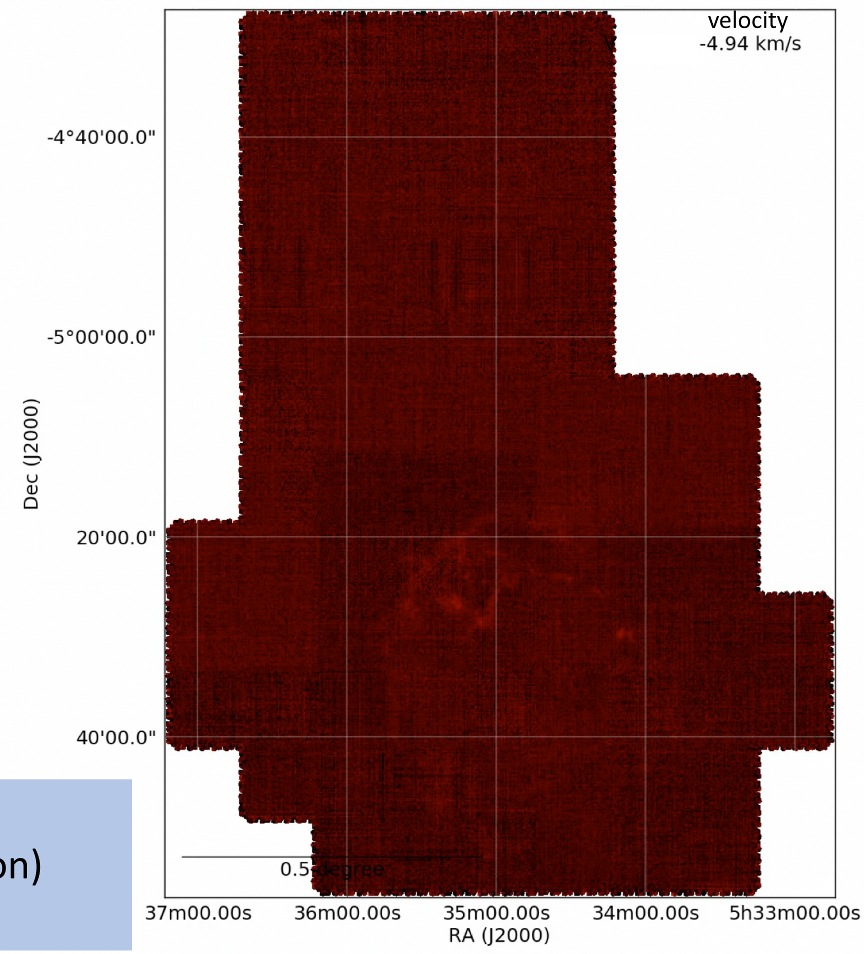


(Pabst et al. & Higgins et al. in prep)

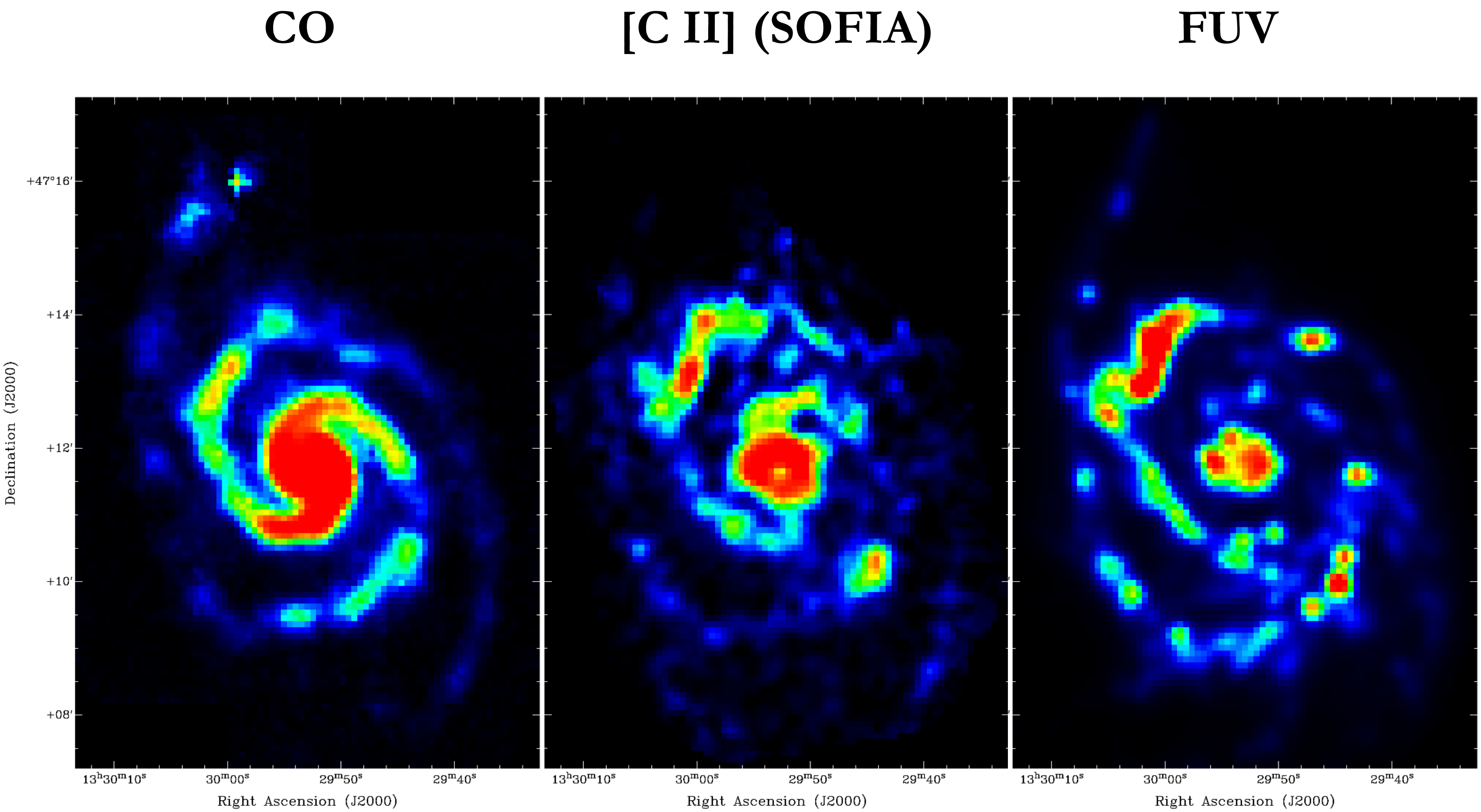
Orion [C II] in 3D

- Bubbles, filaments, colliding flows
- What are the bubble kinematics and energetics? Why do North & South bubbles differ?
- The Orion bar extension
  - A twisted filament?
  - A hydrodynamic feature?
  - Is MHD required?

This project would have required:
~2000 hours of Herschel-HIFI (~8.5 % of the Herschel mission)
~40 hours of SOFIA-GREAT



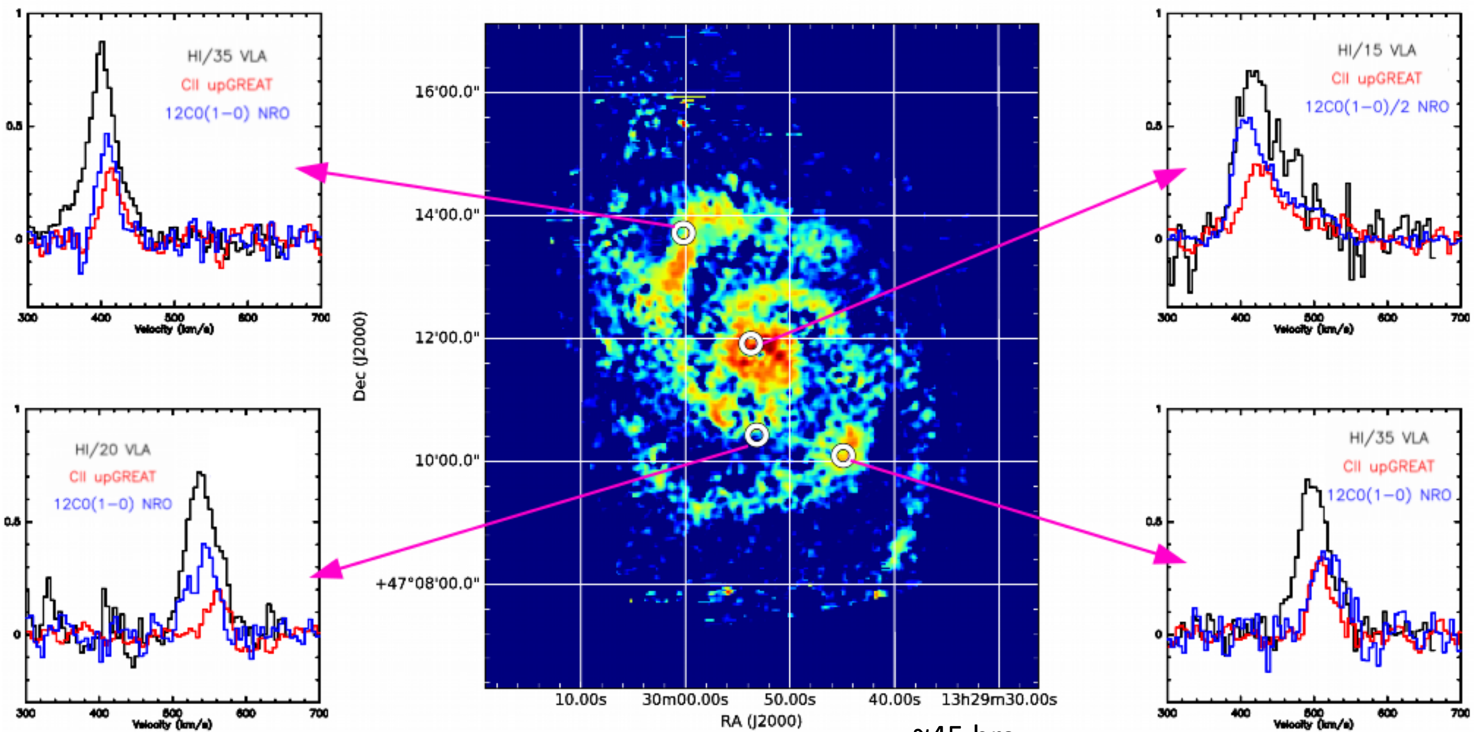
Credit: Tielens



Credit: Pineda

[C II] in M51

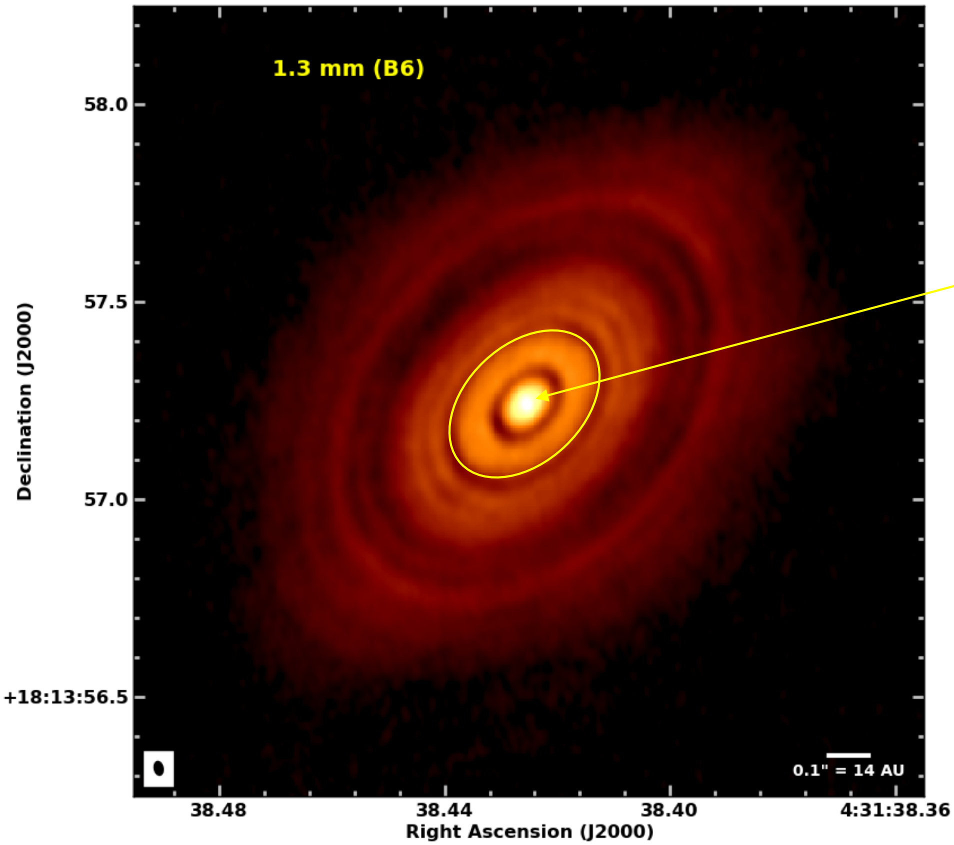
Pineda & Stutzki
(in prep.)

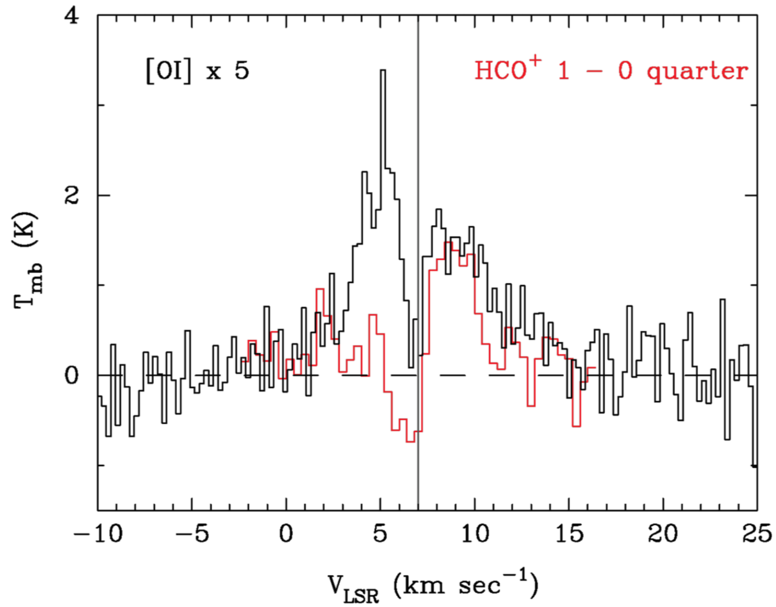


~45 hrs

=> [C II] emission generally separated from CO & HI emission in both space and velocity; Sequence: CO maximum, [C II] maximum, Hα/UV maximum as material flows through spiral arms

Oxygen in the Planet-forming Zone of HL Tau



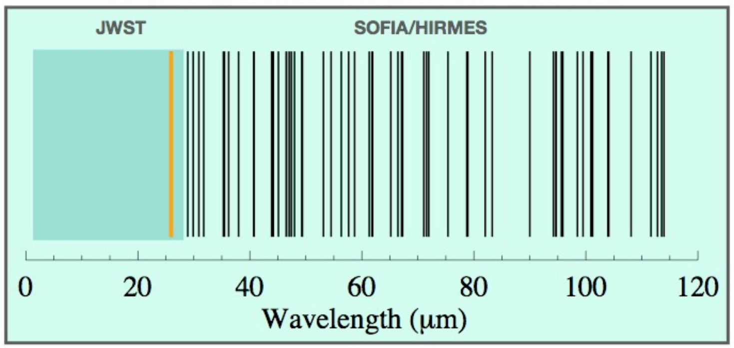


SOFIA atomic oxygen [OI] 63 µm emission (black line). ALMA HCO^+ from the inner 25 AU disk region (red line), shown by the area enclosed by the yellow ellipse to left.

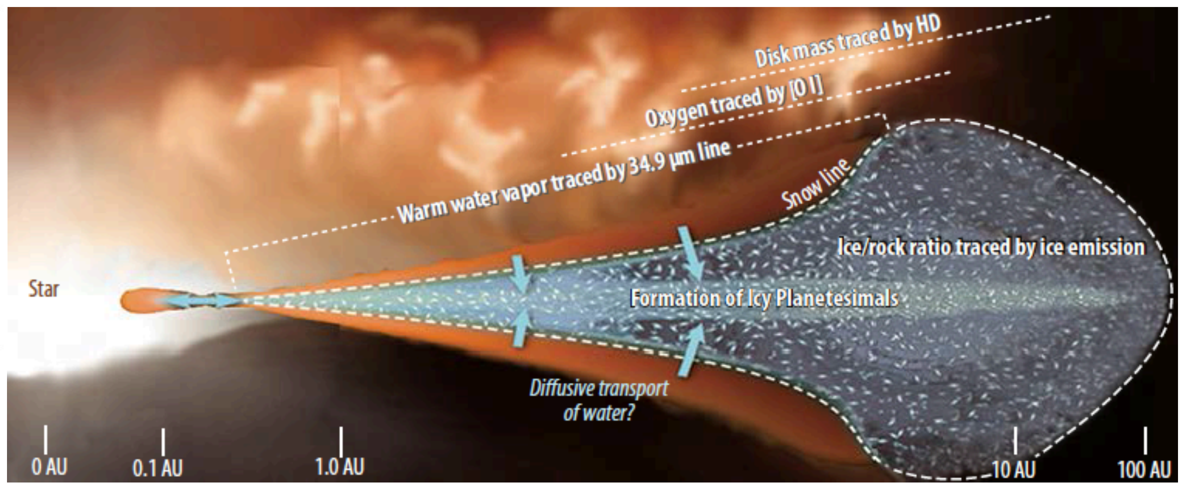
Credit: G. Sandell

HIRMES (HIgh Resolution Mid-infrarEd Spectrometer)

- Spectroscopy with R=600 - 100,000: 25μm – 122μm; mostly diffraction-limited
- Spectral imaging capabilities for a few selected emission lines
  - HD (112μm): How does the disk mass evolve during planetary formation?
  - What is the distribution of O, H_2O-ice, and H_2O-vapor in different phases of planet formation?
  - What are the kinematics of oxygen and H_2O-vapor in protoplanetary disks ?
- 100's of disks within 500 pc are within HIRMES' grasp

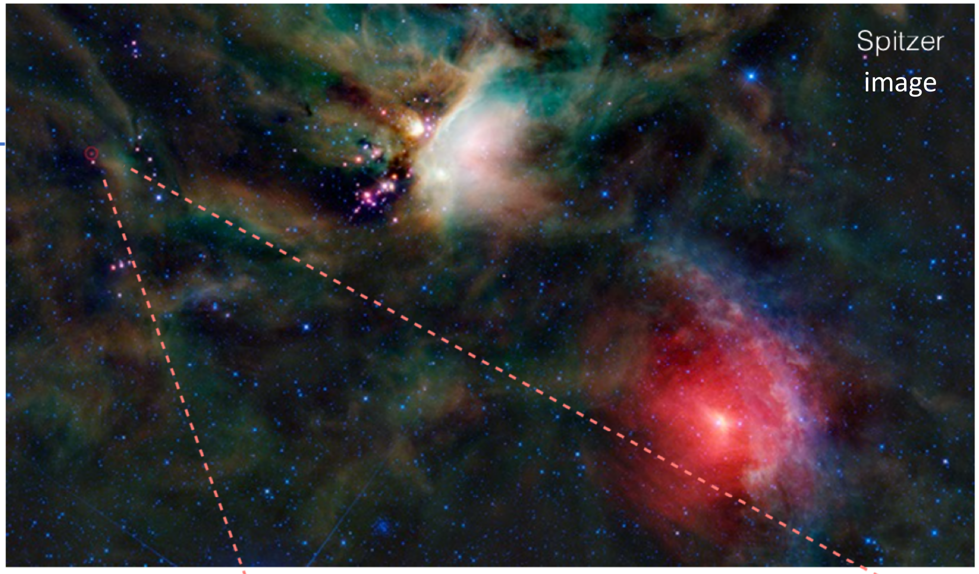


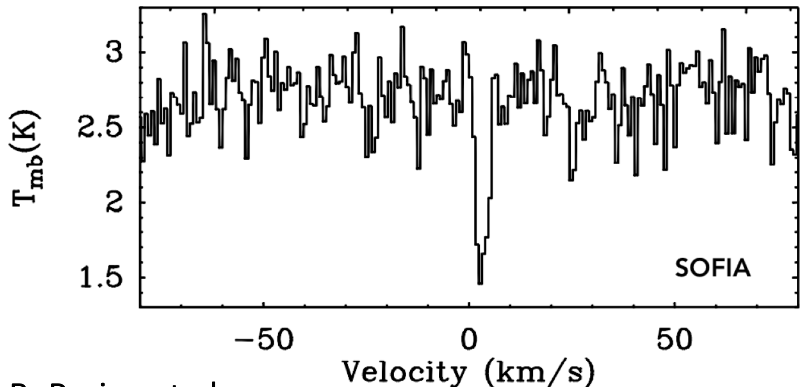
Protoplanetary Disks: Water transitions with E_u/k < 1000 K (figure courtesy G. Melnick)



Path to Water: 1st Cosmic Detection of OD Molecule

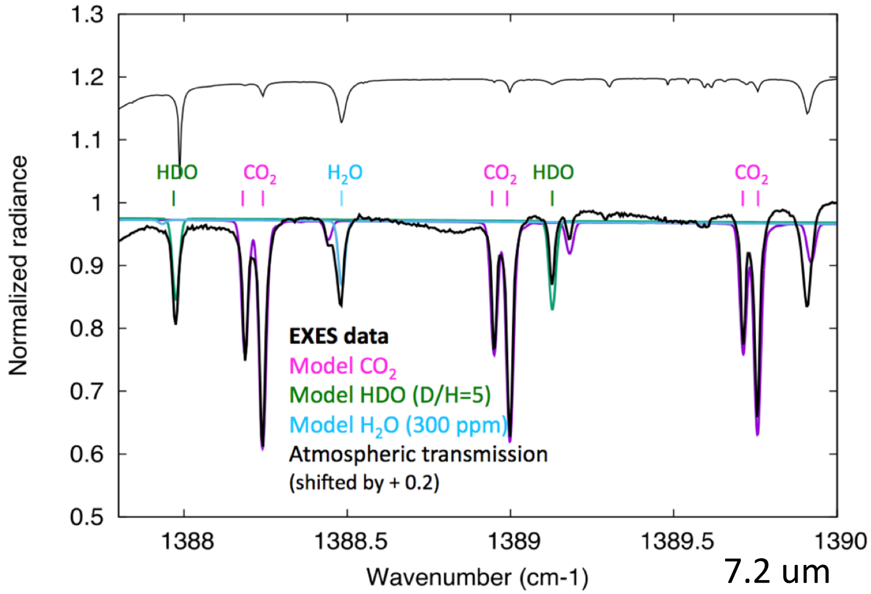
- SOFIA plays a central role in understanding the formation of water in the universe
- Exactly how H and O "find each other" and bond in extreme environments is not well understood, but the formation of OH is an important step
- In cold interstellar clouds, O prefers to combine with heavy hydrogen to make OD rather than OH
- Spectrum shows the first detection of OD outside the solar system
- Brings us a step closer to understanding the origins of the building blocks of life



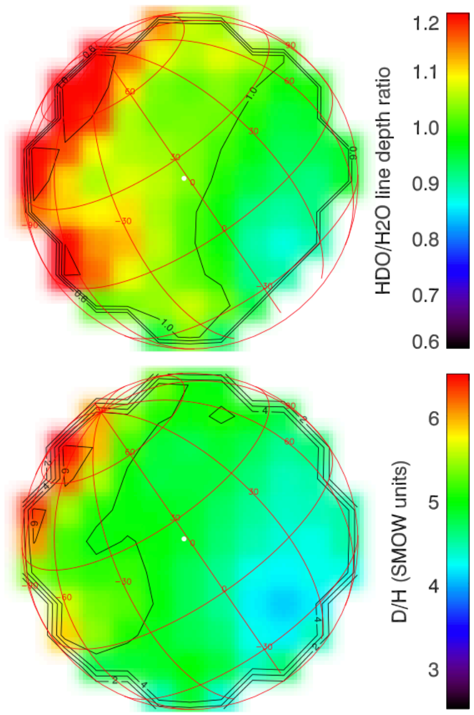


Credit: B. Parise et al.

What happened to Martian Water?



Disk-integrated D/H ratio is 4.4 times the standard Earth oceans' value, consistent with interpretation that liquid water originally present on the Martian surface has been destroyed and has escaped ~2 Gyr ago.



Variation of D/H with location Encrenaz et al. 2016 (above); Mars re-monitored Apr 2014, Mar 2016, Jan 2017 Encrenaz et al 2018

- SOFIA is a modified B747SP aircraft with a 2.7m telescope
- Operates in the optical to sub-millimeter regime
- Offers access to wavelengths inaccessible from the ground or from space any time soon
- Joint Program between the US (80%) and Germany (20%)
- Operated by NASA, DLR, USRA, and DSI
- Full operations began in 2014
- Designed for 20 years of operations (i.e. until 2034)

THE UNIVERSITY OF CHICAGO

Universität Stuttgart

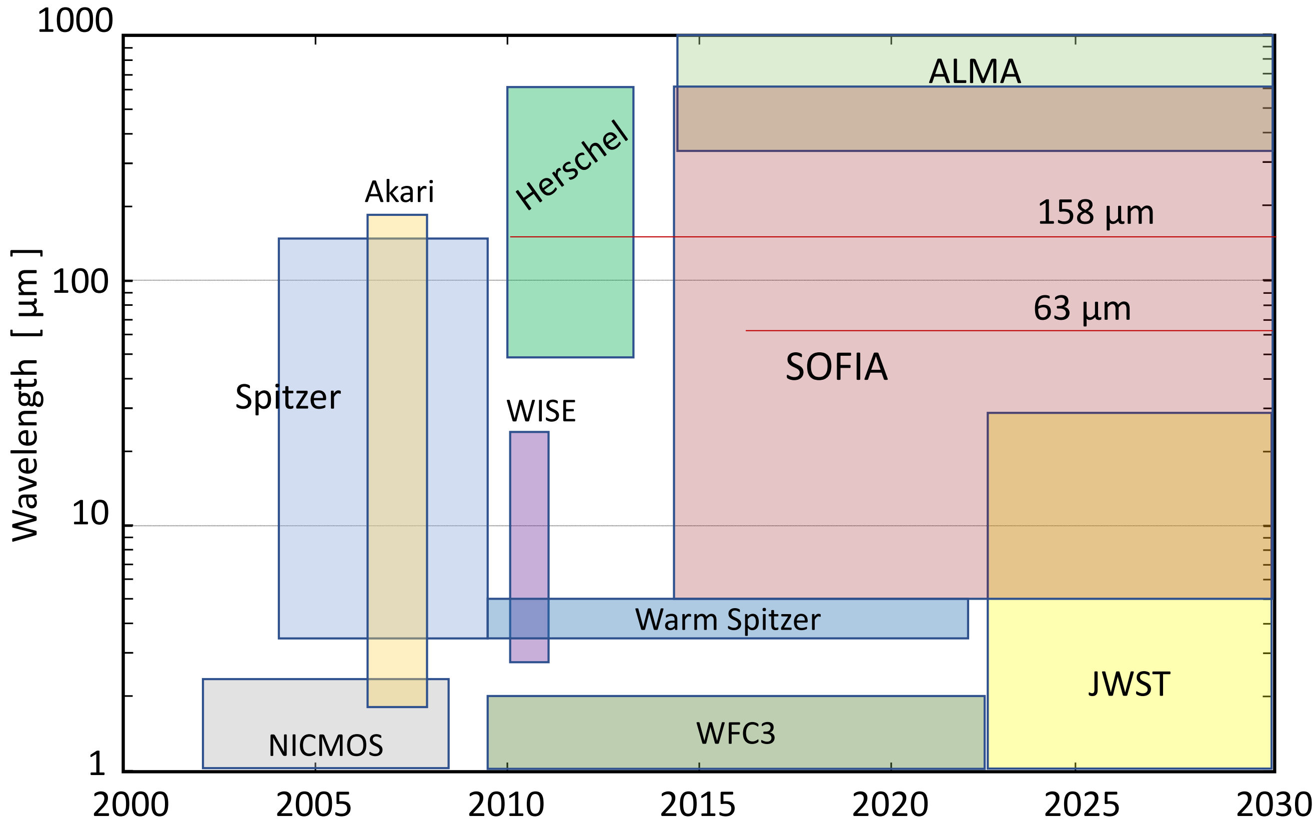
JPL

SOFIA
Stratospheric Observatory For Infrared Astronomy

The SOFIA Era

SOFIA focuses on three fundamental Science Objectives:

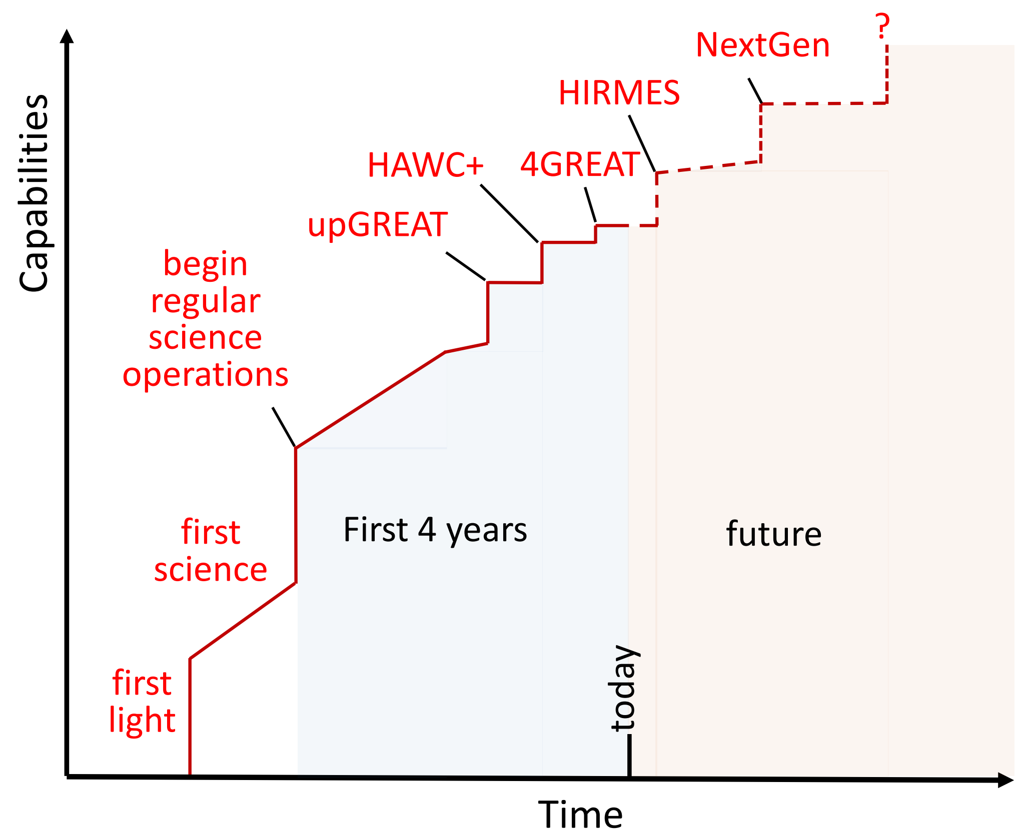
- The Birth of Stars and Planets: Charting the Infall
- The Path to Life: Water, Organics, and Dust through Cosmic Time
- Extreme and Hostile Environments: Stepping Stones to Starbursts and AGN



Capability Profile of SOFIA

With SOFIA, unlike for space missions…

- Hardware repairs & upgrades are possible on a relatively short time scale
- State-of-the-art complex instruments can be added to address current science questions
  - Ample 4K cooling, power, mass, and computing capabilities support early versions of future space hardware
- SOFIA has commissioned and has operated 10 instrument configurations in the last 8 years => 1.2 per year!
- Looking forward, HIRMES will be commissioned in 2019 and a 4th Gen science instrument solicitation is in work.



Plans for Cycles 6 & 7

- Cycle 6 Observing (May 2018 to April 2019) features use of all SOFIA instruments
  - SOFIA just completed 7-week New Zealand deployment with GREAT & HAWC+ (24 flights successfully completed of 25 planned)
  - 80+ flights planned from Northern Hemisphere, including science flights from Seattle during 2019 AAS meeting
- Next Generation Science Instrument proposals due August 1
  - Down-select in October for ~5 month instrument concept studies
- Cycle 7 Observing (April 2019 to April 2020) offers all SOFIA instruments
  - New SOFIA Legacy Program (~100 hours available)
  - ~400 hours open for “US queue” observers
  - Continuing “Thesis Enabling” programs débuted in Cycle 6

The Era of SOFIA Science

- SOFIA is delivering high-quality science
- Instrument upgrades enable SOFIA to expand its capabilities to remain state-of-the-art to serve the international community